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Abstract

We present a high throughput (f/3) visible (3500 – 7000 Å) Doppler spectrometer for toroidal rotation velocity measurements of the Alcator C-Mod tokamak plasma. The spectrometer has a temporal response of 1 ms and a rotation velocity sensitivity of ~10^5 cm/s. This diagnostic will have a tangential view and map out the plasma rotation at several locations along the outer half of the minor radius (r/a > 0.5). The plasma rotation will be determined from the Doppler shifted wavelengths of D_α and magnetic and electric dipole transitions of highly ionized impurities in the plasma. The fast time resolution and high spectral resolving power are possible due to a 6" diameter circular transmission grating that is capable of $\lambda/\Delta\lambda$ ~ 15500 at 5769 Å in conjunction with a 50 μm slit.

I. Introduction

Plasma rotation (both poloidal and toroidal) plays an important role in transport phenomenon and confinement in tokamak plasmas [1,2]. Core measurements have been routinely done on tokamaks using x-ray transitions of He-like Fe or Ar [3,4]. Rotation has been seen to change direction and radial origin during different modes of operation. An example being that upon transition from the L-mode to an EDA or ELM free H-mode the impurity rotation changes from counter-current to co-current and convects inwards from the edge. Particle transport has been correlated to changes in the radial electric field, E_r, that create a shear in the velocity field. This shear is thought to break up turbulent eddies and reduce transport. The MHD fluctuations involved in the changes of radial electric field, E_r, correlated with the L- to H-mode transition have characteristic frequencies of 1 to 100 kHz, or equivalently times scales of 10 μs to 1 ms. A high throughput spectrometer is essential for acquiring a sufficient amount of light to support this temporal resolution. Rotation measurements in the edge are required for understanding the plasma in the H-mode pedestal (r~20 cm) and are desirable to complement the existing core rotation diagnostics. In addition to H-mode studies, changes in plasma rotation have been correlated with the existence of internal transport barriers [5,6,7].

Currently, measurements at the edge of C-Mod are done using a visible Kaiser spectrometer offering a temporal response of 50 ms and a high throughput with an f/# of 1.8. The spectral resolving power of the spectrometer is ~2500 at 4900 Å with 50 μm slit, corresponding to a rotation sensitivity of ~10^6 cm/s. Visible spectrometers are necessary for the edge region because of the relatively low electron temperature (T_e~1 eV – 500 eV) when compared to that from the core (T_e ~ 1 keV) where x-ray spectroscopy dominates. Here we describe a new visible spectrometer with improved spectral and temporal resolution for measuring the toroidal rotation of impurity and majority ion species in the outer half of the Alcator C-Mod tokamak.

II. Doppler Spectrometer and Performance

A schematic of the spectrometer is shown in Fig.1. The main components include a transmission grating, which is on a computer controlled rotation stage, allowing the adjustment of the angle of incidence, two 130 mm diameter transfer optics, an entrance slit and a linear NMOS photodiode array. The detector can be remotely positioned vertically as well as manually rotated in the dispersive (horizontal) plane with the outgoing focusing lens. The high resolution and throughput result from our highly efficient (close to unity) and large (150 mm diameter) grating which is optimized for ~3500 Å.

We have two pair of bi-convex achromat quartz lenses (130 mm diameter) with 50 cm and 40 cm focal length giving an f/# of 3.8 and 3.1 respectively, which are closely matched to the input fibers from C-Mod that have an f/# of ~2.6. To reduce reflection they are coated with MgF_2. The ray tracing program OSLO [8] was used to understand the effects of aberrations on the image quality of such a small f/# lens. The aberrations are minimal. The focus is fairly constant changing by at most 15 mm between 3500 and 7000 Å. Our lenses are suitable for off axis usage up to +/- 1 cm though there is a slight degradation in resolution.

Our spectrometer is designed to match the available fiber optics at the Alcator C-Mod tokamak. In particular, we chose 1 mm round silica/silica fiber bundles, to maximize light into the spectrometer the fiber is transformed into a rectangle (200 μm by

2.5 mm) on the outgoing end. For controlling the resolution we have various slit widths, which can be used (50 - 500 μm). The effective entrance slit and the grating give typical spectral resolving powers of 10000 and 15500 at 3600 and 5500 Å respectively (50 μm slit, f =500 mm). With sufficient light such that a centroid fit can be achieved, this resolving power allows a velocity sensitivity of ~10^5 cm/s, which is 2-10 times smaller than the present capabilities. In general these values can be maximized by choosing the smallest possible entrance angle, α, for a given spectral line. The resolving power is limited to ~15500 due to detector pixel size (25 μm). Additionally, with a bright enough emission transition the temporal response is ~1 ms.

Spectral calibration was performed using a Hg(Ar) pen lamp as well as Pt(Ne) hollow cathode lamp. The groove spacing, d, was determined to be 3944.5 +/- 0.5 Å, both from putting the spectrometer in the Littrow configuration with a He/Ne laser and from careful measurements of the exit angle, β and employing the standard grating equation

$$m\lambda = d(\sin\alpha + \sin\beta) \quad (1)$$

for various spectral features with known entrance angle, α. The lamps were also used to determine the dispersion as a function of the entrance angle, as shown in Fig. 2 where good agreement with Eq. 1 is found. An example of a calibration spectrum is shown in Fig. 3. The measured line width is 0.37 for 5679.6 Å with a 50 μm entrance slit.

III. Detectors and Data Acquisition

Our data system consists of a 1-D sensor and driver circuit from Hamamatsu in conjunction with a multifunction data acquisition card (NI-PCI-6111) from National

Instruments implemented in a G4 Macintosh computer. This system gives us the desired temporal and spectral resolution for our measurements. We have three sensors (Hamamatsus' S3924, S3921 and S3900) the fastest of which has a 1 ms response (50 μm x 2.5 mm x 512 pixels), the largest (50 μm x 5 mm multiplied by 1024 pixels) has a 30 ms response. The third sensor is 25 μm x 2.5 mm x 1024 pixels and can be read at a rate of 2 ms/frame. The wavelength coverage is ~150 Å for a typical setup giving ~0.15 Å/pixels. The driver circuits require a start pulse and a synchronous clock (both TTL). They output a serial data video signal and an A/D conversion trigger. A LabView program was written to control the various timing pulses, the input trigger from the tokamak and data acquisition. The program also controls rotation (grating entrance angle) and translation stages (vertical location of detector and focus of output lens). The sampling rate of the A/D card is 5 Msps, which is more than sufficient to record the fastest signal from the detector (500 kHz). The card has a 12-bit resolution, which for a +/- 5 V range (controllable from +/- 50 V to +/- 200 mV) gives 2.44 mV/bit. The data is digitized into binary and later converted to ASCII and analyzed in IGOR Pro.

IV. Implementation and Planned Measurements

The instrument will be used on C-Mod for toroidal rotation velocity measurements. Passively, using in vessel tangential views described below, we will exploit visible M1 and E1 emission of various intrinsic or gas puffed impurities. Since there is a gradient towards the core in the electron temperature, T_e, within the tokamak and atoms and ions are excited mostly through electron impact excitation within the separatrix, different ionization potentials for different charge states allow rotation measurements to be localized to different radial shells. As this is an integrated chordal measurement, the thickness of the shell determined from a coronal model and the curvature of the toroidal field lines determine the spatial resolution. Transition candidates include B V at 4945 Å just inside the separatrix (~22 cm), Ar X at 5533.4 Å (20-22 cm) and the recycling light of the majority species emission of Balmer $D_{\square}$ at 4860 Å and $D_{\square}$ at 6561 Å. The latter will be used for neutral flow measurements only at the edge region. The second method will use the radially oriented diagnostic neutral beam with two tangential toroidal cross beam views set up in the vessel for charge exchange spectroscopy [9,10,11]. This method allows an improvement in localization of the emission as well as an enhancement of existing transitions. Examples of useful transitions for this method include B V at 4945 Å and B II at 4940.4 Å. The two views cover $0 < r/a < 0.8$ and $0.7 < r/a < 1$. Backlighting of the channels show spatial resolutions of 1-2 cm and 0.5-1 cm respectively along the beam path. There are also poloidal views of the diagnostic neutral beam available. Further measurements that are possible include the poloidal rotation which typically has velocities ten times less than toroidal and ion temperature values from collisional line broadening.

There are other broadening mechanisms that may need to be taken into account [12]. The thermal motion of the ions as well as bulk differences in velocity from the emitters of a single feature from different locations in the line of sight will increase the effective line widths. Also, Zeeman splitting in low Z-ions in the cooler edge region has been shown to cause shifts between the □ and □ components of ~1- 2 Å [13,14,15]. Also, if Doppler broadening is sufficiently small and one or more components of a blended line is independently temperature dependent there is the possibility of an apparent shift. An example is the fine structure components of C VI that leads to a shift in the centroid of 0.15 Å [16]. This may be important for the measurement of small rotation velocities.

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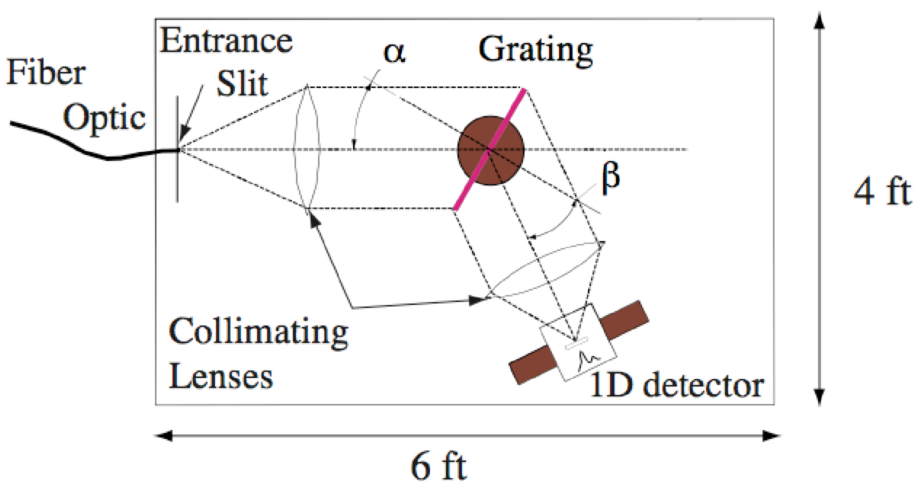
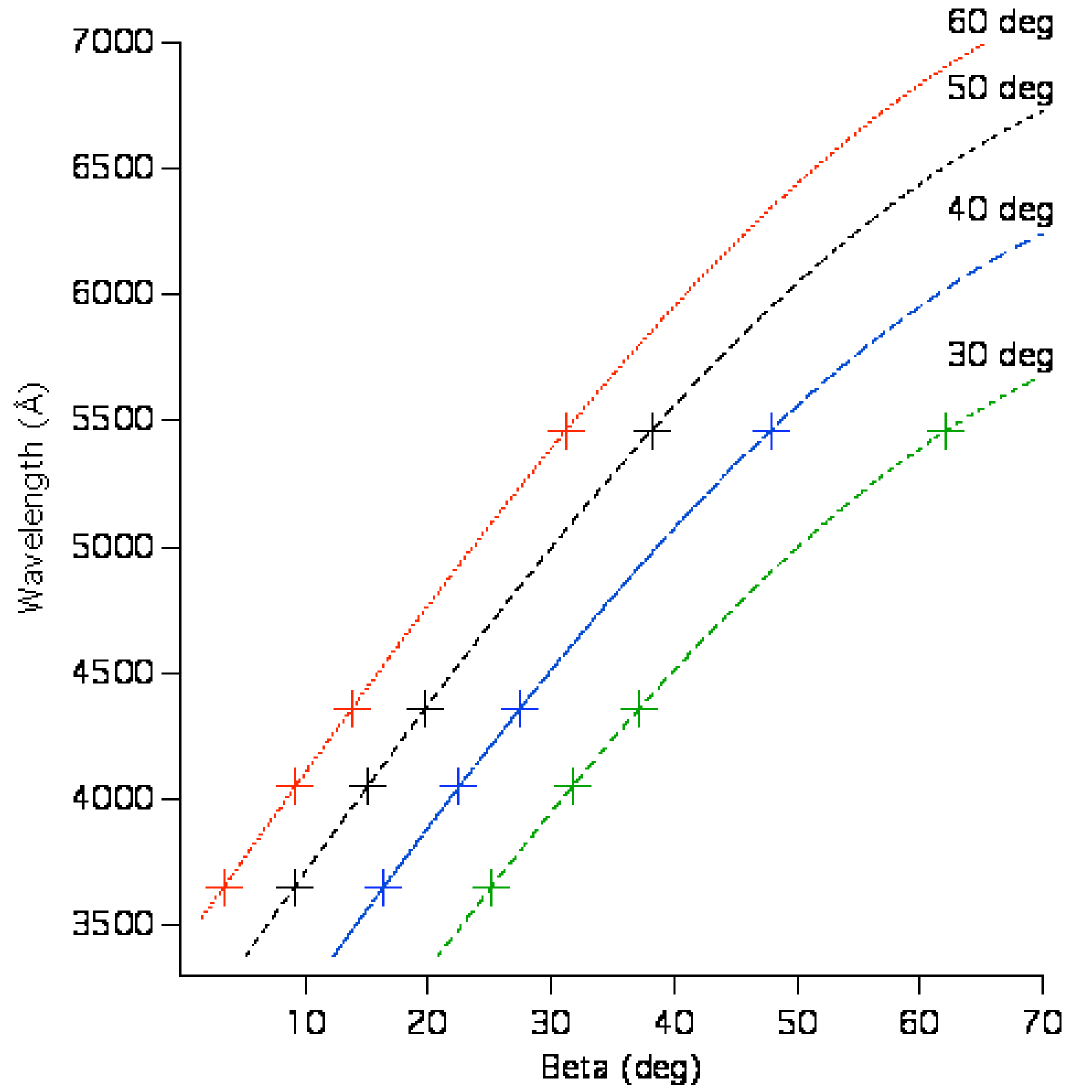


Figure 1, Paper id. F35, Author: A. Graf



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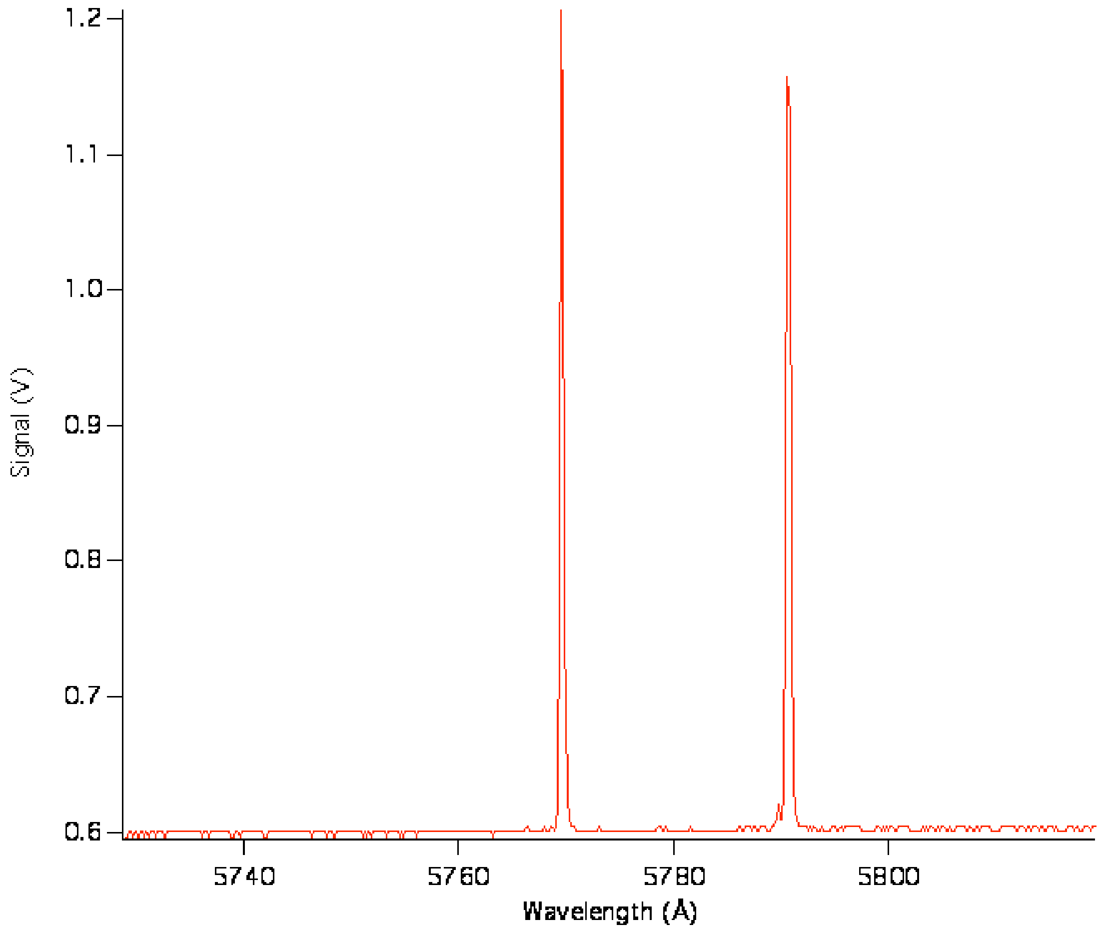

Figure 3, Paper id. F35, Author: A. Graf

Fig. 1 Top view of spectrometer layout, showing the entrance fiber and slit, collimating achromat optics, transmission grating and 1-D detector.

Fig. 2 Wavelength calibration vs exit angle □ (all angles measured from the grating normal). Curves are the grating equation for 4 different entrance angles, □. Four features 3650.2, 4046.6, 4358.4 and 5460 Å from a Hg(Ar) pen lamp are shown to agree with the grating equation.

Fig. 3 Sample spectrum for a Hg(Ar) calibration pen lamp demonstrating spectral resolving powers of 15500 and 14800 for the transitions at 5769.6 Å and 5790.7 Å respectively. The slit width was 50 □m and □ was ~45^{o}.